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The Viability of Photovoltaics on the Martian Surface

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ABSTRACT

The viability of photovoltaics (PV) on the Martian surface may be determined by their ability to withstand significant degradation in the Martian environment. Probably the greatest threat is posed by fine dust particles which are continually blown about the surface of the planet. In an effort to determine the extent of the threat, and to investigate some abatement strategies, a series of experiments were conducted in the Martian Surface Wind Tunnel (MARSWIT) at NASA Ames Research Center. The effects of dust composition, particle size, wind velocity, angle of attack, and protective coatings on the transmittance of light through PV coverglass were determined. Both initially clear and initially dusted samples were subjected both to clear winds and simulated dust storms in the MARSWIT. It was found that wind velocity, particle size, and angle of attack are important parameters affecting occlusion of PV surfaces, while dust composition and protective coatings were not. Neither induced turbulence nor direct current biasing up to 200 volts were effective abatement techniques. Abrasion diffused the light impinging on the PV cells, but did not reduce total coverglass transmittance by more than a few percent.

INTRODUCTION

On the twentieth anniversary of Apollo 11's historic achievement of the first manned landing on the moon, then President Bush proposed, "...a journey into tomorrow, a journey to another planet, a manned mission to Mars." NASA Lewis Research Center was charged with developing plans to provide power on the Martian surface for such a mission. One of the leading candidates as a source of power is photovoltaic (PV) arrays. Calculations indicate that the insolation at the Martian surface is similar to that on the terrestrial surface[1]. A question which, however, has not been as straightforward is the effects of the fine dust which covers the Martian surface. Ultimately, it may be the dust effects which determine whether PV arrays are a viable power source for the Martian surface.

It was against this background that a series of studies was initiated designed to provide experimental evidence on the effects of dust on PV performance on Mars. It was decided that the only practical way to achieve this goal was terrestrial simulation of Martian dust under simulated Martian conditions. The key to these experiments was the existence and availability of the Martian Surface Wind Tunnel (MARSWIT) at NASA Ames Research Center. This paper summarizes the results obtained from several suites of experiments run over a four year period.

METHODS AND MATERIALS

There are a variety of conditions which could affect dust sticking and removal from a photovoltaic surface on Mars. The conditions which were included in these studies were dust composition, particle size, wind velocity, the angle between the wind velocity vector and the array (angle of attack), height above the ground, composition of the PV surface, whether or not there was dust initially on the surface, whether and the wind was "clear" or dust laden. In addition two dust abatement strategies were tried, erection of a "snow fence" in front of the samples, and dc biasing the samples.

Samples

No decision has yet been made about the type of PV cell which will be used in the early Mars exploration missions. It was assumed the PV cells will probably be protected by a coverslip and that SiO_2 is a likely coverslip material. Hence, most of the tests were done with 2.5 cm square, 0.13 mm thick glass coverglass. In order to determine if there might be a better choice to minimize dust effects, some of the coverglass were ion beam sputter coated with candidate protective coatings including SiO_2, polytetrafluoroethane (PTFE), a 50 percent mixture of SiO_2 and PTFE, indium tin oxide (ITO), or diamond-like carbon (DLC). Table I summarizes the coatings.

TABLE I — Photovoltaic Cell Coatings Tested

COATING†	THICKNESS	DEPOSITION	SUBSTRATE
SiO_2	650 Å	ion beam	glass
PTFE	1000 Å	ion beam	glass
PTFE/SiO_2	1000 Å	ion beam	glass
ITO	1000 Å	ion beam	glass
DLC	1000 Å	ion beam	glass

†abbreviations defined in text

The samples were mounted in specially designed sample holders by means of foil tabs which stretch across two corners, and by a third foil tab attached to a removable pin (figure 1). The idea was to try to maintain the flat surface as much as possible. Samples were held at angles of 0° (horizontal), 22.5°, 45°, 67.5°, or 90° (vertical) from the wind tunnel floor. The holders could also be held horizontally for initial dust deposition or for optical transmittance measurements.

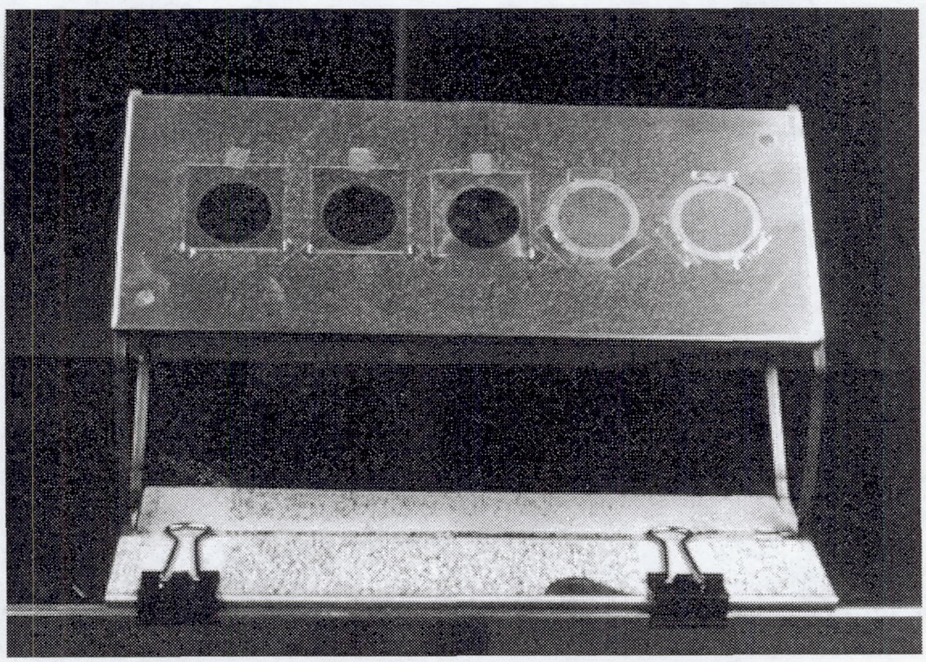

Figure 1.—Sample holder of the type used to test photovoltaic coverslips.

Optical transmittance measurements were made by sliding the sample into a transmittance measuring device (TMD) shown in figure 2. In the TMD an incandescent light source was suspended above the sample, and the sensing head of a Coherent Model 212 Power Meter was beneath the sample. Absolute transmittance measurements were converted into percent transmittance measurements.

In the case of the initially clear samples the ratio of the final to initial transmittance (T_f - T_o) was calculated. Note that this function ranges from zero (when so much dust has accumulated that no light can be detected) to one (when no dust has been deposited).

In the case of initially dusted samples, the situation is more complex. Measurements were made before and after the samples were dusted (T_o and T_d respectively), and after the dusted samples were subjected to the MARSWIT tests (T_f). The amount of dust cleared from the sample was evaluated using a dust clearing parameter, which was defined as the ratio of the transmittance change on exposure of the dusted samples (T_f - T_d) to that of the transmittance change upon dusting (T_o - T_d). This function is constrained to vary from zero (no clearing of the dust by the wind) to one (complete clearing of the dust by the wind). If there is a net accumulation the dust clearing parameter becomes negative. Note then that the values of zero and one have different meaning for the initially dusted and initial clear case.

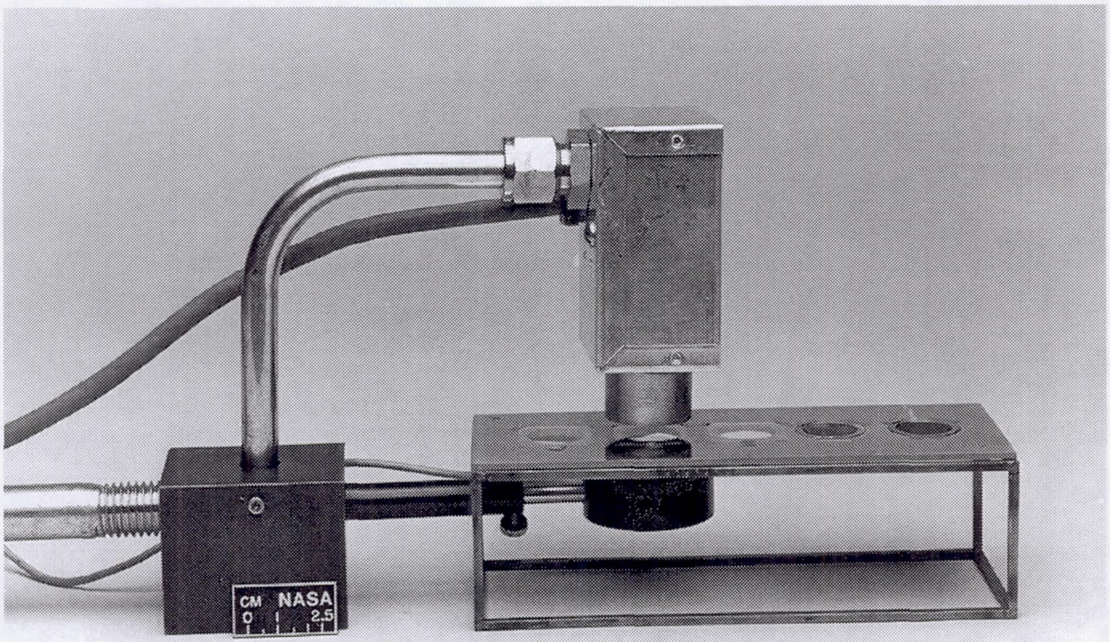

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Figure 2.—Transmission Measuring Device (TMD) used to test transmission of light through photovoltaic coverslips.

In order to verify that our coverglass measurements were valid tests, conventional SiO_2 covered and uncovered N/P silicon PV cells (Spectrolab) were affixed to the sample holders described above in place of one of the coverglass. All PV cells were mounted on 45° sample holders. Damage was assessed by inspection using optical and scanning electron microscopes. The illuminated (AM0) cell characteristics were also measured using a Spectrolab X-25L xenon arc solar simulator calibrated by an aircraft calibrated silicon reference standard.

Martian Dust Simulants

The composition of the Martian dust is not well understood. The elemental composition was determined by the Viking landers[2], and based on the optical properties developed from terrestrial materials analogs have been proposed.[3] The Viking biology experiments, however, dramatically showed that the chemistry of the dust is unique to Mars. It should be noted that the purpose of these experiments was not to try to accurately simulate the Martian soil, but to try to determine how sensitive dust clearing is to dust composition. Thus, a variety of dust compositions were used to simulate various aspects of the Martian dust. The chemical composition of these simulants, as well as the elemental composition determined from the Viking Landers is found in Table II.

TABLE II — Composition of test dusts

MINERAL	VIKING LANDERS	OPTICAL POLISH	TRAP ROCK	IRON OXIDE	ARTIFICIAL GLASS
SiO_2	44.6 %	6.6 %	46.6 %	0.0 %	53.5 %
Fe_2O_3	18.1	0.6	13.0	100.0	21.7
MgO	8.3	0.0	6.1	0.0	9.9
Al_2O_3	5.7	89.0	16.6	0.0	6.8
CaO	5.6	0.0	11.1	0.0	0.0
TiO_2	0.9	3.0	2.0	0.0	1.1
Na_2O	?	0.0	2.3	0.0	6.7
Cr_2O_3	0.0	0.6	0.0	0.0	0.0
MnO	0.0	0.0	0.3	0.0	0.0
P_2O_5	0.0	0.0	0.1	0.0	0.0
K_2O	0.0	0.0	1.1	0.0	0.3
CO_2	?	0.0	0.1	0.0	0.0
TOTAL	83.3 %	99.8 %	99.3 %	100.0 %	100.0 %
SIZE	0.1 - 2000 μm	7 - 25 μm	5 - 20 μm	0.5 - 2.5 μm	5 - 100 μm

The distribution of particles sizes in the Martian atmosphere and on the loose surface has not been narrowly constrained by experiments to date. Best estimates of particle size distributions suggest 0.1 to 2000 μm diameter particles at the Viking lander sites.[4] The smallest particles (0.1 to 10 μm) remain suspended in the atmosphere indefinitely, and the sand size particles (60 to 2000 μm) will not rise more than a few meters from the surface. Particles in the intermediate sizes (5 to 100 μm) are expected to be elevated during dust storms and quickly settle out onto, among other things, PV surfaces.

An 1800 grit aluminum oxide based optical polishing grit (American Optical Company) was the first test dust. The important property of the optical polishing grit is its low tendency to agglomerate with moisture in the air. The particle sizes, ranging from 7 to 25 μm, were chosen to be in the range where the particles would be elevated on Mars during times of high wind speed, but which would settle out on surfaces after the winds subsided.

A finely ground basalt called "trap rock" was the second simulant. The Martian soil appears to be basaltic in nature, so a typical basalt was thought to be appropriate. Its grey-green color is an indicator, however, that it differs from the orange dust of the Martian surface. The particles sizes, 5 to 20 μm were similar to the optical polishing grit.

The third simulant was finely ground iron (III) oxide (Fe_2O_3). The Martian soil is known to have a high iron content, one where iron is in high oxidation states. Its particle size was an order of magnitude smaller than the first two dusts.

The final simulant was an glass manufactured (Ferro Corp., Independence, Ohio) to approximate the composition of the Martian dust as closely as possible. This was sifted into several different size ranges and served to enable study of the effects of particle size over a range of about 5 to 100 μm. The larger particles (greater than about 75 μm) might better be described as sand.

The dust was applied to the samples by elevating it within an enclosure by a stream of dry air, and allowing it to settle out on the sample surfaces. The techniques is described in detail elsewhere.[5] The uniformity and extent of the dust deposition were monitored optically. For most runs, the ratio of the transmittance after dusting to before (Td) was between 0.4 and 0.7. The specular transmittance was used as a probe of the extent of occlusion and abrasion. Power is also generated in PV cells from diffuse light, and so the specular transmittance cannot be converted directly to PV performance. However, Katzan et al. have related coverglass transmittance in the TMD to N/P silicon PC cell performance at AM0.[6] Their data, reformatted in figure 3, indicate that the normalized transmittance correlates with PV power (calculated from the I-V curves) to within the error of the measurement.

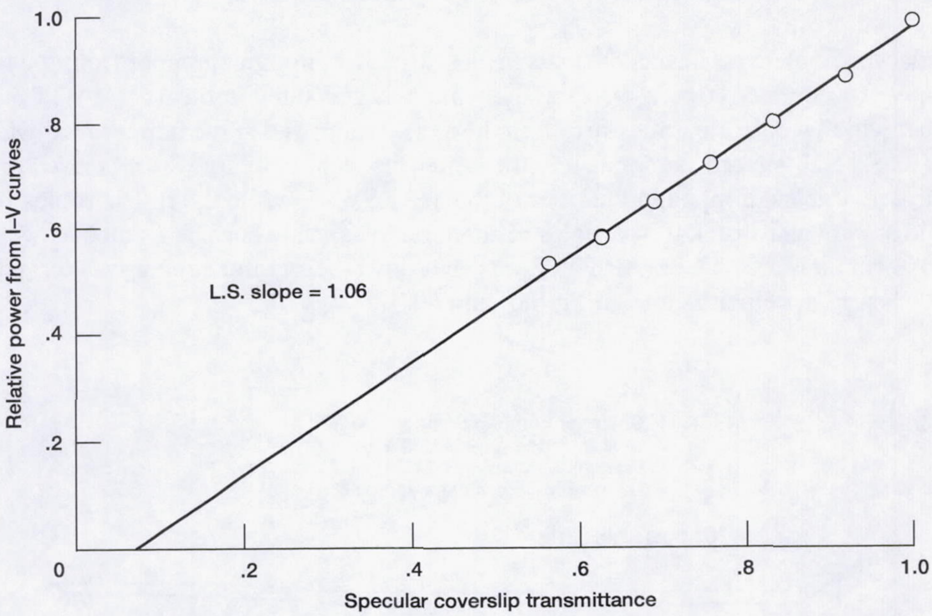

Figure 3.—Relationship between coverslip transmittance as measured in this study and PV power calculated from I-V curves on N-doped on P-doped silicon cells at AMO.

Experimental Conditions

The first suite of experiments had as its goal to determine whether dust which would settle out on photovoltaic surfaces would be blown away by the tenuous Martian winds. The effect of angle of attack, height from the surface, and various coatings on cover glasses were also investigated. Optical polishing grit was used as the test dust. Wind tunnel velocities varied from 10 to 124 m/s (22 - 277 mph).

A principal focus of the second suite of experiments was the effects of different dust types. Thus, many of the experiments from the first suite of experiments were carried out using trap rock or iron (III) chloride instead of the optical polishing grit. Glass and plastic cylindrical sample holders were also introduced at this stage. A horizontal "snow fence" was tried as an abatement technique. Wind velocities varied from 30 to 95 m/s (67–213 mph).

A the third set of experiments investigated the effects of basaltic dust being blown onto the surfaces. Thus, a series of experiments using initially clear and initially dusted samples were subjected to simulated Martian dust storms. Dust blown wind velocities varied from 19 to 97 m/s (43–217 mph).

The fourth set of experiments investigated the effects of particle size on the dust clearing and depositing properties. For these experiments a Ferro glass Martian simulant was sifted so that a dust which had a composition relevant to the Martian surface and available in different particle sizes was used. Wind velocities varied from 23 to 116 m/s (51–259 mph).

In the fifth set of experiments complete PV cells were tested (as opposed to coverglass), and dome geometry was tested. The domes were hemispheres and semispheres with a radius of about 10 cm. The PV cells were run neutral, and also biased up to ±200 V dc.

The winds on Mars were simulated using the Martian Surface Wind Tunnel (MARSWIT) at the NASA Ames Research Center. The MARSWIT is a flow through wind tunnel 14 m in length with a 1 by 1.1 by 1.1 m test section located 5 m from the tunnel entrance. It is located within a 3000 m^3 vacuum chamber which can be pumped down to a few mbar. It is capable of developing wind speeds in excess of 100 m/s at 10 mbar. Its characteristics are described in detail elsewhere.[7]

In order to simulate a Martian dust storm, dust was fed through a hopper from the top of the MARSWIT, near its entrance (figure 4). First the wind was generated in the MARSWIT at a velocity well below that which would clear dust off of predusted samples. Then the hopper feed was started, dropping the dust into the air stream. Immediately thereafter the wind velocity was increased to the test conditions. The larger particles dropped to the floor of the MARSWIT, while the fine particles were carried along the wind stream and struck the particles resident on the sample surfaces, much as would happen during a dust storm on Mars. The MARSWIT was shut down before the hopper was turned off, so there was not time when high velocity clear air hit the samples.

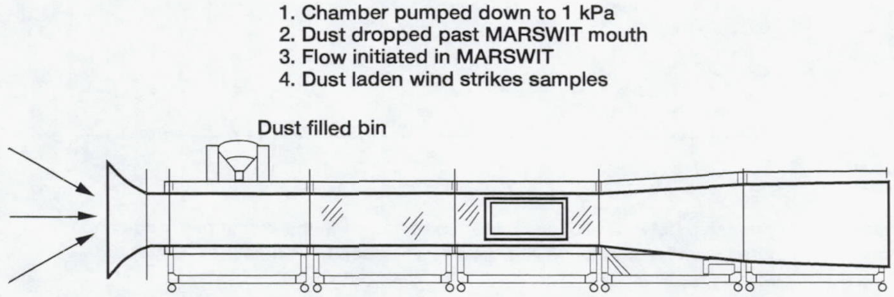

Figure 4.—Schematic drawing of the Martian Surface Wind Tunnel (MARSWIT).

Some of the samples were gold coated and imaged in a Cambridge Model 200 Scanning Electron Microscope (SEM). Photomicrographs were made of samples both before and after dust was cleaned from the samples. Particles size distributions were determined using a Cambridge Quantimet 900 image analyzing computer.

RESULTS AND DISCUSSION

Dust Clearing from Initially Dusted Samples

The first issue to be addressed revolved around the ease of clearing dust from a PV surface by the winds on Mars. Although there is evidence of high wind velocities on Mars,[8] the atmospheric pressure is only about one percent that of Earth. Thus force per unit area exerted by the wind, the dynamic pressure

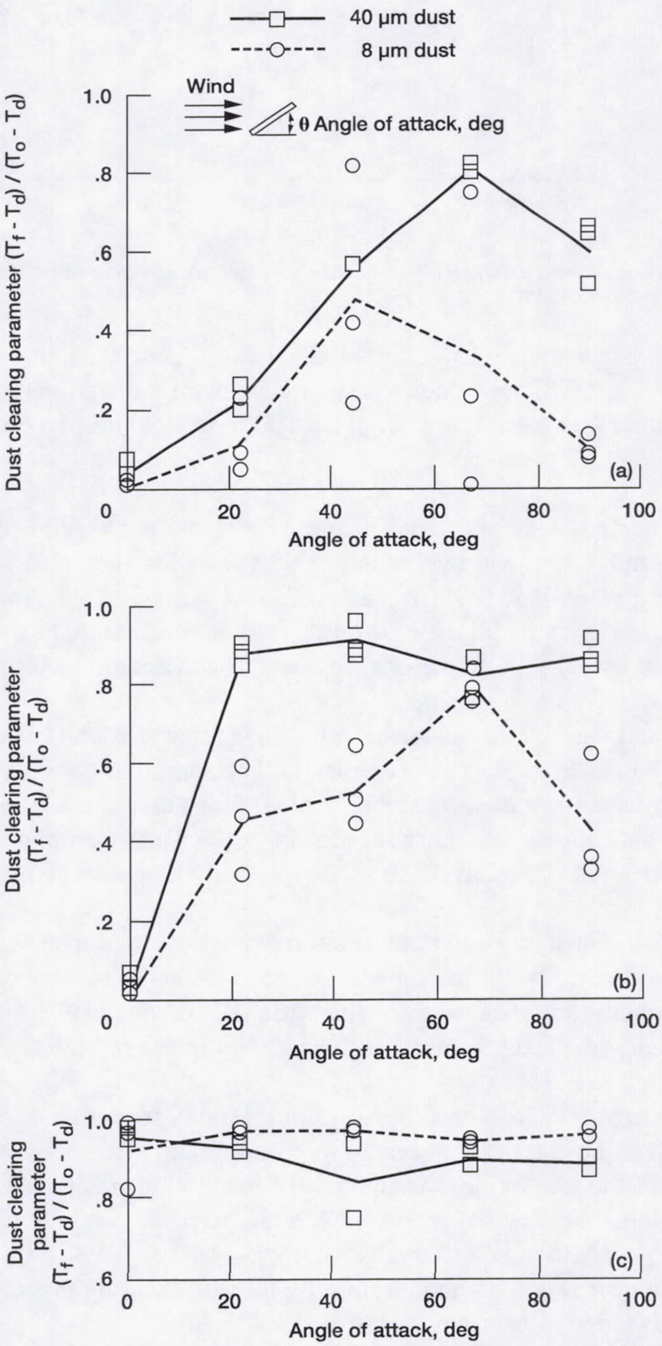

Figure 5.—Dust clearing parameter as a function of angle of attack initially dusted samples in clear winds in the MARSWIT. (a) 23 m/s. (b) 40 m/s. (c) 95 m/s clear winds in the MARSWIT.

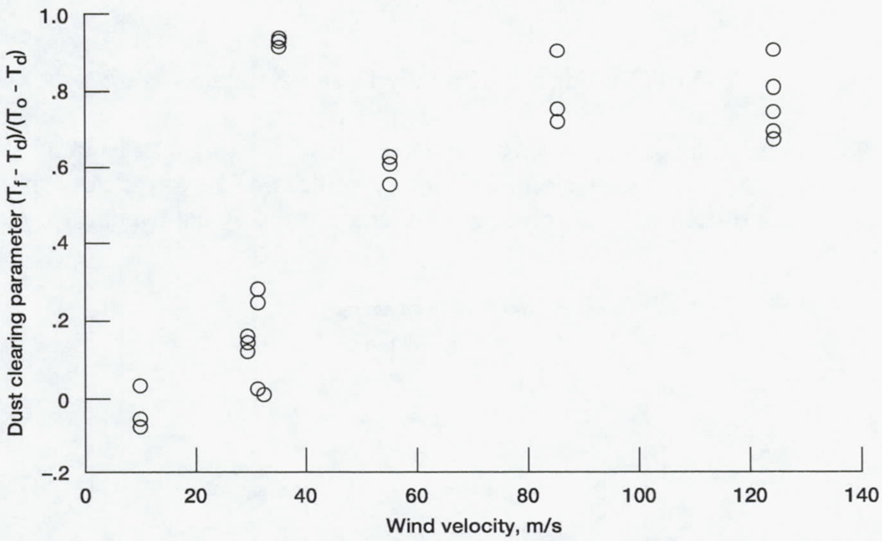

Figure 6.—Dust clearing parameter in clear wind as a function of wind velocity for 45° angle of attack in the MARSWIT.

($^1/_2\rho v^2$, where ρ is the gas density, and v is the wind velocity), is only about one percent that of comparable wind velocities on Earth. Since velocity is squared, a Martian wind velocity ten times that of Earth's will give a similar dynamic pressure. For example, a 100 mph wind on Mars is comparable to a 10 mph wind on Earth.

As might be expected, wind velocity was the most important variable determining wether dust was cleared from the samples. At wind velocities of 95 m/s and higher, dust was effectively cleared (dust clearing parameter greater than 0.9) from all surfaces (figure 5c). The maximum wind velocity recorded by the Viking Landers was a bit over 30 m/s.[9] It should be noted, however, that the Viking Lander data are averaged over 1 minute periods, so gusts of wind could well have exceeded 30 m/s.

Another important variable for dust clearing efficiency was found to be the angle of attack. If the samples were tilted with respect to the wind (that is, not horizontal), the threshold clearing velocity (the minimum wind velocity to remove dust from the surface) drops dramatically, to 30 to 40 m/s. This is illustrated in figure 6 which shows the threshold clearing velocity for samples held at a 45° angle. When the angle of attack reaches 90° (vertical) the threshold velocity increases again, to 55 to 85 m/s.

Clearing of basaltic dust in place of aluminum oxide dust produced similar results, as illustrated in figure 7. The threshold velocity for basaltic dust at 45° appears to be between 30 and 40 m/s, within the same range as aluminum oxide. However, when iron (III) oxide dust was used the threshold clearing velocity was much higher, between 85 and 95 m/s, as shown in figure 8.

The surface chemistry of iron oxide differs considerably from that of either aluminum oxide or basalt, and that may affect the result. However, a more important effect may well be the particle size. The mean particle size of the iron oxide was an order of magnitude smaller than that of the other two materials, and so one would expect that the threshold velocity to be between two and three times higher based on particle size effects alone,[10] and that is what was observed. From this test it appears that the surface chemistry of the dust is not key in determining the dust clearing threshold velocity. Given the uncertainties in the knowledge of Martian dust, this is fortunate.

The particle composition tests did make obvious that another important variable was dust particle size. Smaller particles have greater surface volume ratios, so it is expected that surface interactions, such

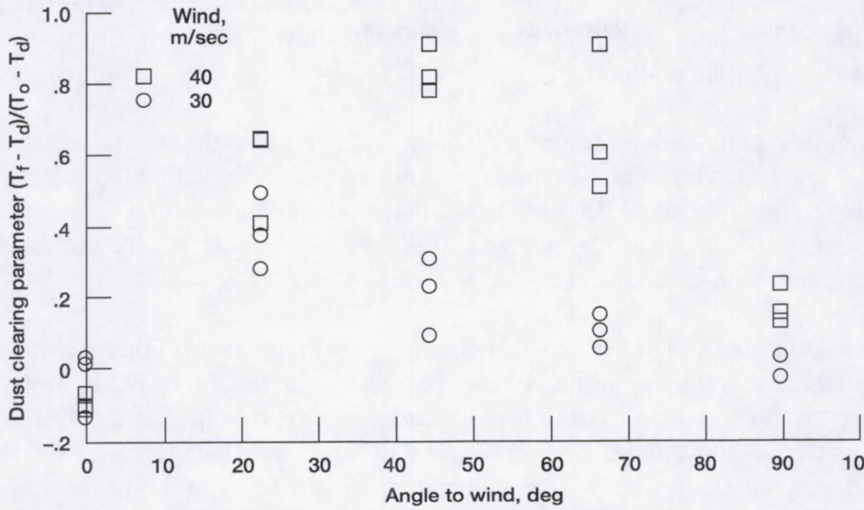

Figure 7.—Clearing of basaltic dust from initially dusted coverslips.

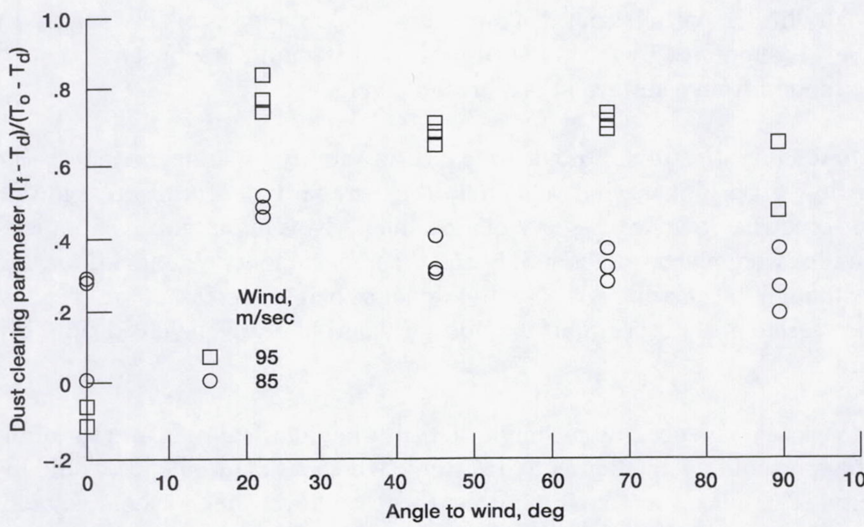

Figure 8.—Clearing of iron (III) oxide dust from initially dusted coverslips.

as adhesion, would be more important for small particles. Experiments bear out that the threshold clearing velocity is dependent on the particle size. Small particles (10µm and below) did not clear efficiently at 40 m/s, where as larger particles (30 µm) did. This clearly shown in figure 5 where the threshold clearing velocity of particles of the same composition under the same conditions, differing only in their size, are compared.

The largest particle sizes used, being larger than 75 µm, might be better described as sand than dust. Particles smaller than this, because of their high adhesion to the sample plates, could be tipped to 90° or even inverted with no significant loss of particles. Particles larger than 75 µm however, would slide off of the plates when tipped to a high angle. Our measurements indicate that the angle of repose for these particles was about 27°. However, these measurements were done in a gravity field of 1.0 g. On Mars, with a gravity of 0.377 g, a sliding force equal to that created by 27° in 1.0 g could not be developed at any angle, so this material would be expected to exhibit dust-like behavior. In fact, any particles with an angle of repose greater than about 22° would be expected to exhibit dust-like behavior. Therefore, particles larger than 75 µm were not used to dust sample plates, but were used in the wind

stream to examine the effects of particle size on clearing, deposition, and abrasion. The deposition data for angles greater than 27° is not expected to be representative, however, of deposition on the Martian surface since the particles would slide off.

The threshold clearing velocity for initially dusted samples in clear Martian wind is dependent on the angle of attack (figure 5). Horizontal examples require very high velocities (85 m/s), whereas those cocked at 45° angle require only about 35 m/s. The actual angular dependence is somewhat broad with 22.5° and 67.5 sample clearing to a similar degree. At 90° (vertical) however, the threshold clearing velocity is somewhat higher than at the intermediate angles.

Given the angular dependence of the dust clearing, one might suspect that the mechanism of detachment would involve the rolling or sliding of dust particles, followed by their becoming airborne. For the most part, however, this did not appear to be the case. Photomicrographs of the dust layer remaining on the dusted glass surfaces subjected to 35 m/s winds at different attack angles showed no directionality to the dust removal. Only on the samples with an attack angle of 22.5° could it be discerned from the photographs the direction of wind arrival. This was further confirmed by photographs of the cylindrical samples subjected to the same conditions. Only when both the wind velocity and the angle of attack were very low was there any appreciable rolling or sliding of the particles. Thus, turbulence at the surface must act to aerodynamically lift the particles out in a direction which is approximately normal to the surface (Figure 7). This view is supported by the classical models of Bagnold in which aerodynamic lift plays a key role in particle motion from a surface at the threshold velocity.[11]

This lead to the investigation of the relative clearing ability of laminar and turbulent flow over the samples. Laminar flow gives higher wind velocities which are fairly uniform across the surface. Turbulent flow results in somewhat lower average velocities, but perhaps higher local velocities. In the first experiment the samples were placed at about 3, 6, and 9 cm from the wind tunnel floor, all within the boundary layer. Although the clearing was slightly higher as height increased, the effect was small. Samples which were tested at about 5 cm off the floor of the MARSWIT behaved similarly to those held 50 cm off the floor.

Turbulence was also induced by placing a "fence" of cylindrical rods in front of the samples at a wind speed near the threshold, in an attempt to determine whether the turbulence would lower the threshold clearing velocity. The fence was found to raise rather than lower the threshold velocity.

A wide variety of photovoltaic cell coatings were tested to determine if coatings could be used to lower the threshold clearing velocity. Because of probable differences between the simulant and actual Martian dust this test may have limited applicability, but it was hoped that trends might be observed. The results are presented in detail elsewhere,[12] but the general result is that the coatings did not change the threshold clearing velocity appreciably.

Dust Adhesion to Initially Clear Samples

Dust was found to stick on initially clear samples which were exposed to simulated Martian dust storms. Once again the important variables were wind velocity and angle of attack (figure 8). Transmittance decreases as angle of attack increases from 0° (horizontal) to 90° (vertical). There was less than 5 percent degradation in the transmittance of samples when the attack angle was 0° over a wide range of wind velocities. In contrast, those with an attack angle of 90° suffered a 17 to 36 percent degradation. Note that higher velocity winds produced larger degradation.

Transmittance of the coverglass can actually be degraded by two mechanisms, occlusion and abrasion. Abrasion was not found to be significant until the wind velocity was about 85 m/s. As is apparent in figure 9, abrasion increased with angle of attack. At 97 m/s wind driven dust horizontal samples were essentially undamaged while vertical samples sustained substantial damage. However, even the highly damaged samples lost little of their transmission when the occluding dust was removed. None of the samples lost more than about 3 percent (Table III). In fact, in a study of PV coverglass pitting by micrometeoroids, it was found that in a totally pitted coverglass (no original surface remaining) the transmission only drops by about 5 percent. The transmitted light does go from specular to diffuse. This will not be a problem in conventional PV cells, but this could be a serious difficulty for solar concentrator cells.

Table III – Performance of PV Cells

	Cover glass	Initial dust µm	Wind dust µm	Wind speed m/s	Pitted by SEM?	AMO Eff %	Tf/To 45° cover
PV–1	none	30	none	23	no	9.6	1.00
PV–2	none	10	none	32	no	9.1	1.00
PV–3	SiO_2	30	none	95	yes	9.6	0.97
PV–4	SiO_2	10	none	96	yes	9.5	0.97
PV–5	none	10	15	23	no	---	1.00
PV–6	none	none	15	23	no	9.3	1.00
PV–7	SiO_2	10	15	89	yes	8.5	0.98
PV–8	SiO_2	none	15	89	yes	9.4	0.95

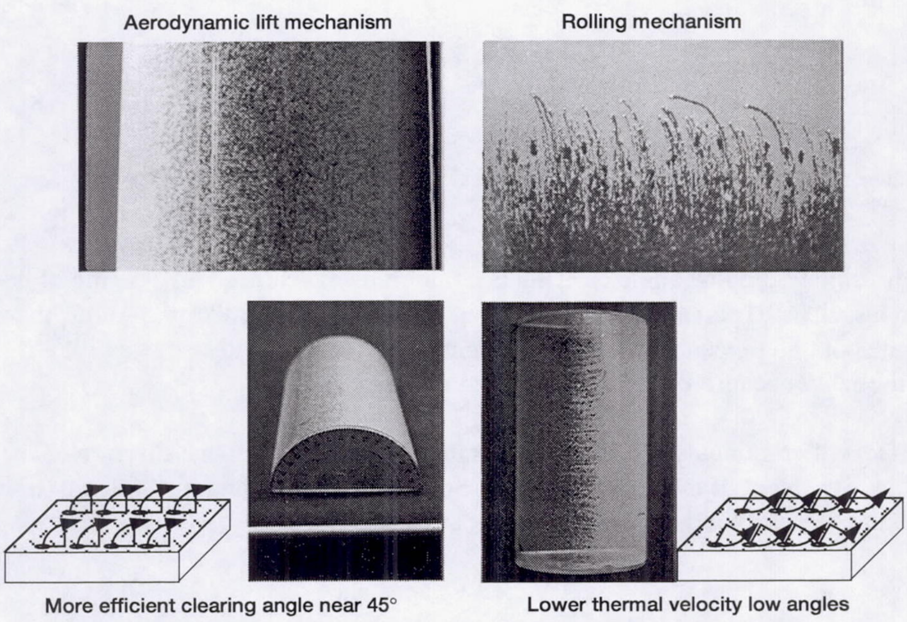

Figure 9.—Different dust removal mechanisms operate under different conditions.

Dust Adhesion to Initially Dusted Samples

The most likely scenario for photovoltaic cells which are emplaced on the surface for long periods of time is that they will have a coating of dust, and will be occasionally swept by dust laden wind. All samples experience a net dust clearing when predusted samples were exposed to dust laden wind. At low velocity (19 m/s) the net clearing increased with angle from horizontal through vertical (figure 10). Even though this was well below the threshold clearing velocity for clear air, all samples had a net clearing. The horizontal samples cleared by somewhat less than 20 percent, but the vertical samples cleared by about 90 percent. Thus, as wind driven particles collide with the surface, they will more likely knock particles off of the existing surface than stick themselves. This will lead to a dynamic equilibrium in which dust thickness will vary with wind velocity and entrained particle concentration. Particle size distributions also support the dynamic equilibrium model. Although the dust storm experiments only lasted about 15 seconds it was found that the proportion of small particles was larger in the predusted samples exposed to dust laden wind. Larger particles which were initially on the sample surface were blown off, and smaller particles from wind were blown on.

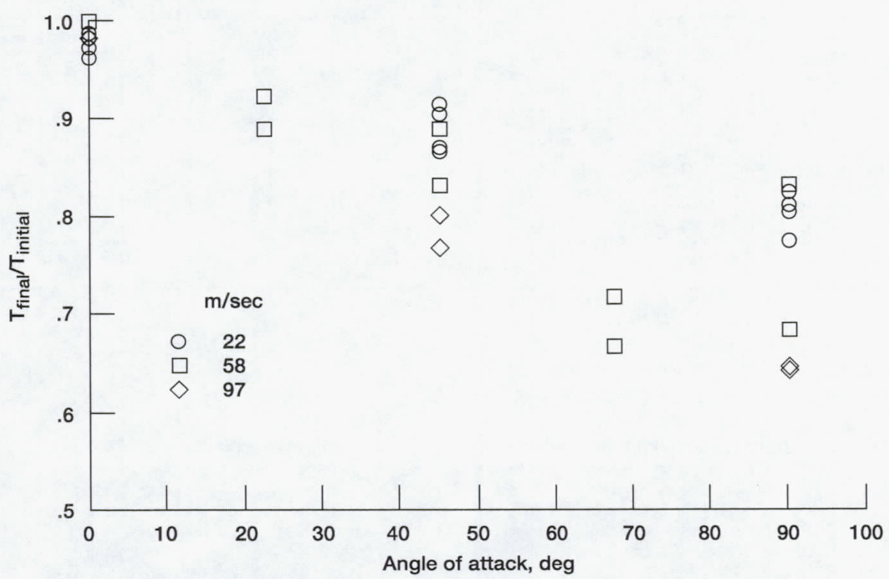

Figure 10.—Change in coverslip transmittance as a function of angle of attack for initially clear coverslips subjected to dust laden wind.

At high velocity the low angle clearing become more efficient. The clearing of horizontal plates improved from less than 20 percent for 24 m/s to about 80 percent at 100 m/s. At 45° there was an improvement from about 50 percent to about 70 percent. The vertical plates showed little if any increase in dust clearing, probably because the deposition rate increased also.

The effects of entrained sand size particles (75 μm) were somewhat different. There was a net clearing to about 80 percent of the clean plate value during both high and low velocity tests. Further, this value was found to be nearly independent of attack angle.

PV Cell Performance

Coverglass transmittance, though thought to be a good predictor of PV cell performance, is not synonymous with it. The degradation of transmittance due to occlusion is thought to reasonably reflect the degradation in PV power. This is what was measured by Katzan, et al. as noted earlier. Abrasion,

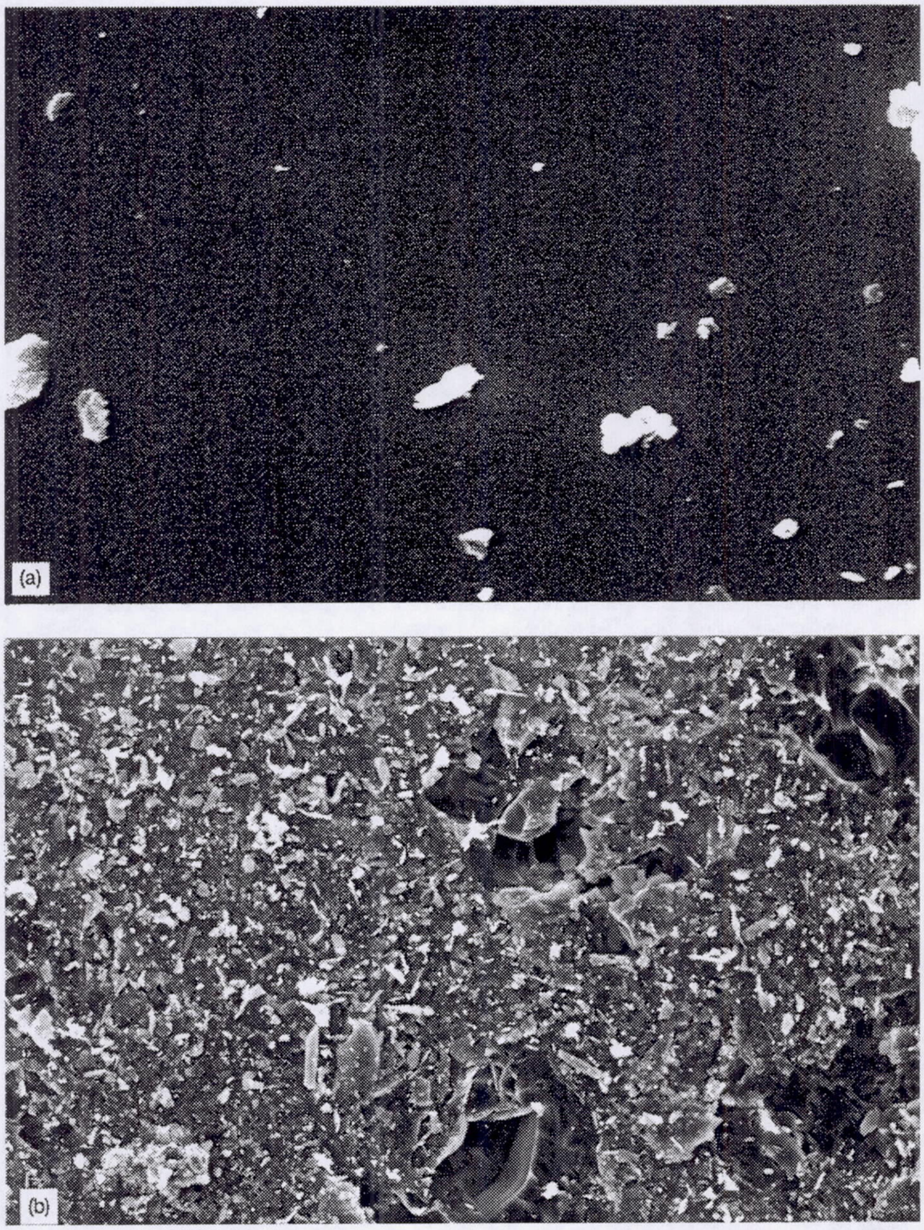

Figure 11.—Scanning electron micrographs of coverslip surfaces subjected to 97 m/s dust laden wind. (a) Angle of attack = 0°. (b) Angle of attack = 90 °.

however, might not be accurately reflected in these results. Thus, PV cell characteristics were actually measured in a few cases. Abrasion of PV cell surfaces was only observed in those samples subjected to 89 m/s winds and higher. The abrasion pits in the SiO_2 coverglass looked like those in PV coverglasses when imaged under the SEM. The efficiencies calculated form the current-voltage characteristics of the PV cells subjected to the MARSWIT were measured after these tests (Table III). Although the efficiencies were not determined before the tests, the sample subjected to 23 m/s wind showed no visible signs of damage, and thus were thought to reflect the initial conversion efficiencies. Given that assumption, there was no significant loss in the efficiencies of any of the PV cells. Bowman, et al. have reported degradation in PV cell performance from coverglass abrasion caused by hypervelocity impact of about

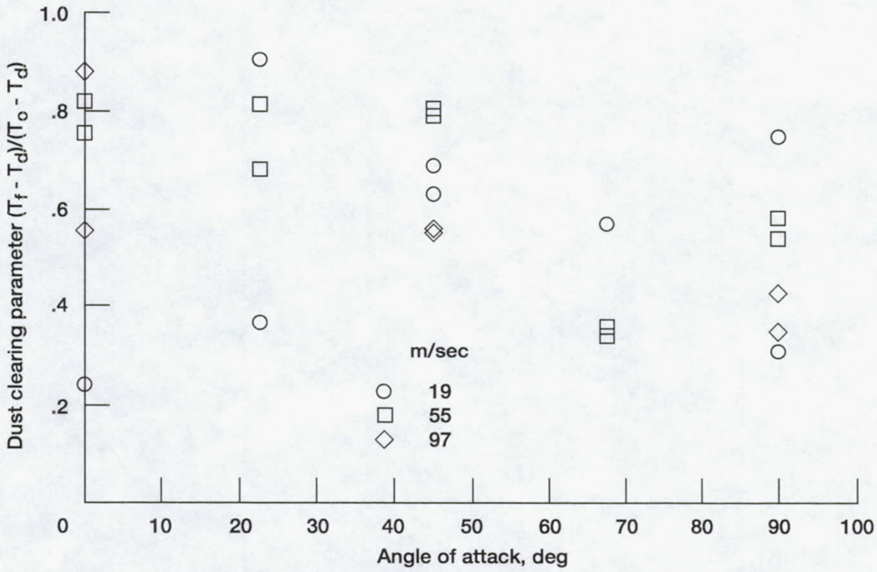

Figure 12.—Change in coverslip transmittance as a function of angle of attack for initially dusted coverslips subjected to dust laden wind.

5 percent.[13] These tests had very high impact densities which perhaps set an upper bound for the abrasive component of cell degradation. Wade reported that erosional effects on the contacts could be an important factor in degradation[14] but, with covered cells and no inter-cell contacts, such effects were not observed in this study.

Cells without coverglasses were also tested in similar conditions (see Table III). No significant differences were observed between those cells with coverglasses and those without. It would be noted, However, that none of the unprotected cells were tested at high wind velocity.

During use conditions PV arrays often develop a voltage bias with respect to their surroundings. Since electrostatic interactions are expected to be an important dust adhesion mechanism, it was thought that this bias might affect the threshold clearing velocity. Thus, PV cells were biased up to +200 V or –200 V dc in an attempt to determine this effect. No differences between the biased and unbiased cells were observed.

CONCLUSIONS

The degradation of PV coverglass on the Martian surface due to dust was investigated by a series of experiments conducted in the MARSWIT. The effects of dust composition, particle size, wind velocity, angle of attack, and protective coatings on the transmittance of light through PV coverglasses were determined. Both initially clear and initially dusted samples were subjected both to clear winds and simulated dust storms in the MARSWIT.

It was found that the ability of clear winds to remove dust from surfaces increases as wind velocity and particle size increase, and reaches a maximum when the angle of attack is roughly 45° (±25°). Threshold clearing values for samples held at 45° angle were about 35 m/s when the particle size was in the 7 to 25 μm range. This is about the same as the highest winds recorded by the Viking Landers. Dust composition and protective coatings had little effect on the threshold velocity.

The amount of dust deposited in artificial wind storms also varied with particle size, wind velocity and angle of attack. Smaller particles were more likely than larger to be deposited, or more probably,

less likely to be removed once deposited. Similarly, lower wind speeds resulted in more net deposition. Unlike the dust clearing behavior, more dust was deposited as the angle of attack increased from horizontal to vertical. Occlusion was not sensitive to dust composition.

It was also found that wind velocity, particle size, and angle of attack are important parameters affecting occlusion of PV surfaces which were initially dusted and then subjected to dust laden wind. The higher the wind velocity and higher the angle of attack the more net clearing of dust from the surfaces was achieved. The threshold clearing velocity was much lower with dust laden wind, occurring below 22 m/s in all but the horizontal sample cases. A dynamic model of smaller particles being attached while larger are removed was supported by a net decrease in the particle sizes which remained on the samples.

The brief search for effective abatement techniques was successful with neither induced turbulence nor direct current biasing up to ±200 volts being effective. Perhaps the best abatement is control over the attack angle. Horizontal deployment of PV arrays which are expected to operate over the long term should be avoided. Tilting the arrays into the wind even at a relatively shallow angle (20°) could pay large dividends.

Significant abrasion was only seen in samples subjected to high velocity (> 85 m/s) winds. This is much higher than the winds recorded by the Viking Landers. Abrasion diffused the light impinging on the cells, but did not reduce total coverglass transmittance by more that a few percent. Concentrator PV cells and mirrors for solar dynamic power systems would be much more vulnerable to the effects of abrasion.

PV cells were substituted for coverglass in a few of the experiments with the general result being to validate the coverglass data.

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The viability of photovoltaics (PV) on the Martian surface may be determined by their ability to withstand significant degradation in the Martian environment. Probably the greatest threat is posed by fine dust particles which are continually blown about the surface of the planet. In an effort to determine the extent of the threat, and to investigate some abatement strategies, a series of experiments were conducted in the Martian Surface Wind Tunnel (MARSWIT) at NASA Ames Research Center. The effects of dust composition, particle size, wind velocity, angle of attack, and protective coatings on the transmittance of light through PV coverglass were determined. Both initially clear and initially dusted samples were subjected both to clear winds and simulated dust storms in the MARSWIT. It was found that wind velocity, particle size, and angle of attack are important parameters affecting occlusion of PV surfaces, while dust composition and protective coatings were not. Neither induced turbulence nor direct current biasing up to 200 volts were effective abatement techniques. Abrasion diffused the light impinging on the PV cells, but did not reduce total coverglass transmittance by more than a few percent.

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